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Simulations Varying Projectile Sabot Front-Bell Stiffness and Its Effect on Dispersion

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Simulations Varying Projectile Sabot Front-Bell Stiffness and Its Effect on Dispersion

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Abstract

This report extends the results of XM881 dispersion modeling done previously by changing the front-bell spring stiffness. The models studied show the effect on dispersion of the XM881 when changing the sabot front-bell stiffness by a power of 10 softer and stiffer. These two modified cases are compared to the nominal case. The basis for this work comes from modeling and experimenting. All mathematical modeling results come from the BALANS program, a finite element lumped-parameter code that has the capability to model a projectile being fired from a gun. This program also has the unique feature of an automated statistical evaluation of dispersion. This study shows that softening the sabot front bell has more of an effect on dispersion.

Table of Contents

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List of Figures

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List of Tables

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1. Introduction

The primary objective of these balloting simulations is to show the effect on dispersion due to hypothetical stiffness changes applied to the sabot front-bell bore rider of a projectile. The BALANS program from Arrow Tech Associates [1] is used to perform the balloting analysis. The BALANS program has a stochastic target impact dispersion analysis module. In the case of the armor-piercing, fin-stabilized, discarding-sabot (APFSDS) kinetic energy (KE) round studied here, the projectile front-bell stiffness is interfaced to the gun barrel by spring stiffness parameters. In this study, the spring stiffness values of the front bell are varied by powers of 10. This is done to demonstrate the bore-rider stiffness effect on dispersion.

The dynamic state of a projectile at shot exit is determined in part by the in-bore launch disturbances experienced by the projectile as it traverses the length of the barrel. A contributing factor is the initial misalignment of the projectile's principle axis and center-of-gravity (CG) offset with respect to the bore centerline. As the projectile is driven axially down bore by the propellant gas pressure, it is also forced to travel a path that is determined by static and dynamic curvature of the gun tube. Tube droop in the vertical plane is a gravity-induced static curvature. The bore straightness is a static curvature resulting from the manufacturing process. The firing of the gun produces an array of complex interdependent events. Axial travel of the projectile and propellant gas pressure impart recoil forces on the gun and result in a slight bending of the barrel. The projectile reacts in flexure to the massive barrel, and the barrel responds to the projectile loads. This dynamic lateral path then becomes the fluid boundary condition or forcing function for projectile balloting.

When studying an APFSDS KE round, such as the XM881 projectile, the response of the sabot petals can determine the linear and angular motion of the projectile at muzzle exit. By studying the differences in dispersion of the projectile with a change in sabot front bore-rider stiffness, generic trends in dispersion may be determined. The experimental study [2] of a generic 25-mm round in 1989 showed that a stiffer front bore-rider could provide a lower dispersion. The experimental study was limited in number of rounds fired.

The XM881 is an early prototype round that was selected for experimental study because of its similarity to the M919 used with fielded systems. One fielded system of major interest is the M242 25-mm autocannon found on the Bradley fighting vehicle (BFV). This system is ideal for setup in a small-caliber range, such as the Aerodynamics Range Facility of the U.S. Army Research Laboratory (ARL) at Aberdeen Proving Ground (APG), MD.

One of the methods for complementing the experimental process in the understanding of dispersion is to perform mathematical modeling jump tests. The previous study on dispersion did this by modeling the modified XM881 projectile [3] as fired. The modeling was a collaborative effort by the Aerodynamics Branch of ARL and Arrow Tech Associates in South Burlington, VT.

The previous study concluded that the total dispersion computed is reasonable, despite the difficulty in exactly modeling the experiment. Mathematical modeling can be a quick way of investigating a hypothetical question of, "what is the effect on dispersion if," the front-bell part of the sabot is softer or stiffer.

Therefore, in this study, all parameters from the previous study [3] are held constant except for the front-bell-spring parameter. In this hypothetical situation, it seemed reasonable to bias the selection of front-spring parameter to ensure that results would indeed show a difference. Thus, the softer spring parameter is a power 10 less than the nominal spring value, and the stiffer spring parameter is a power of 10 greater than the nominal value. These changes in stiffness are much larger than can be expected in an actual design.

2. Analytical Approach

BALANS [1] simulates the dynamic response and interaction of a flexible projectile and a flexible gun tube during in-bore travel. It also includes the effects of a curved bore profile. The simulation utilizes individual models of the projectile and gun tube in a time-step iterative solution. Pertinent motion and load data are periodically saved during the analysis to produce

selective summary graphical displays. BALANS takes advantage of the interior ballistics simulation and CG offset calculations of PRODAS [4] and an automatic lumped-parameter modeling capability to assist in building a BALANS model.

The analytical procedure utilized in BALANS presupposes that the projectile is initially misaligned within the gun tube due to manufacturing tolerances. During firing, this misalignment produces secondary forces, causing transverse displacement and yawing motion of the projectile as it travels from the breech to the muzzle. The resulting yaw angle, angular rate, and transverse velocity at muzzle exit are then analyzed for their effect on dispersion. Note that BALANS calculates the total dynamic state of the projectile (yaw, yaw rate, and transverse velocity) at muzzle exit. This includes the effect of the tube motion on the projectile.

Figure 1 contains a flow diagram of the stochastic method for predicting dispersion. Whether trying to predict dispersion on a new design or solving a dispersion-related problem on a current design, the approach is very similar. It begins with gathering basic technical information, such as manufacturing dimensional data, assembly drawings, and/or specifications or test results. This information is critical to building an accurate model of the projectile.

This information can be obtained from finite-element calculations or structural testing or gleaned from statistical process control (SPC) information. Even if working with a new projectile design for which there is no production history, it is valuable to obtain SPC information for a similar design or a projectile in order to make estimates. Since some of the inputs to this approach are statistical in nature, the historical SPC data provides a foundation from which to derive the statistical information.

The last type of information required for predicting dispersion is test and/or measurement. This includes bore centerline measurements, bore-sight errors inherent within a test fixture or bore-sight tool, known sabot discard issues from tests of similar sabots, etc.

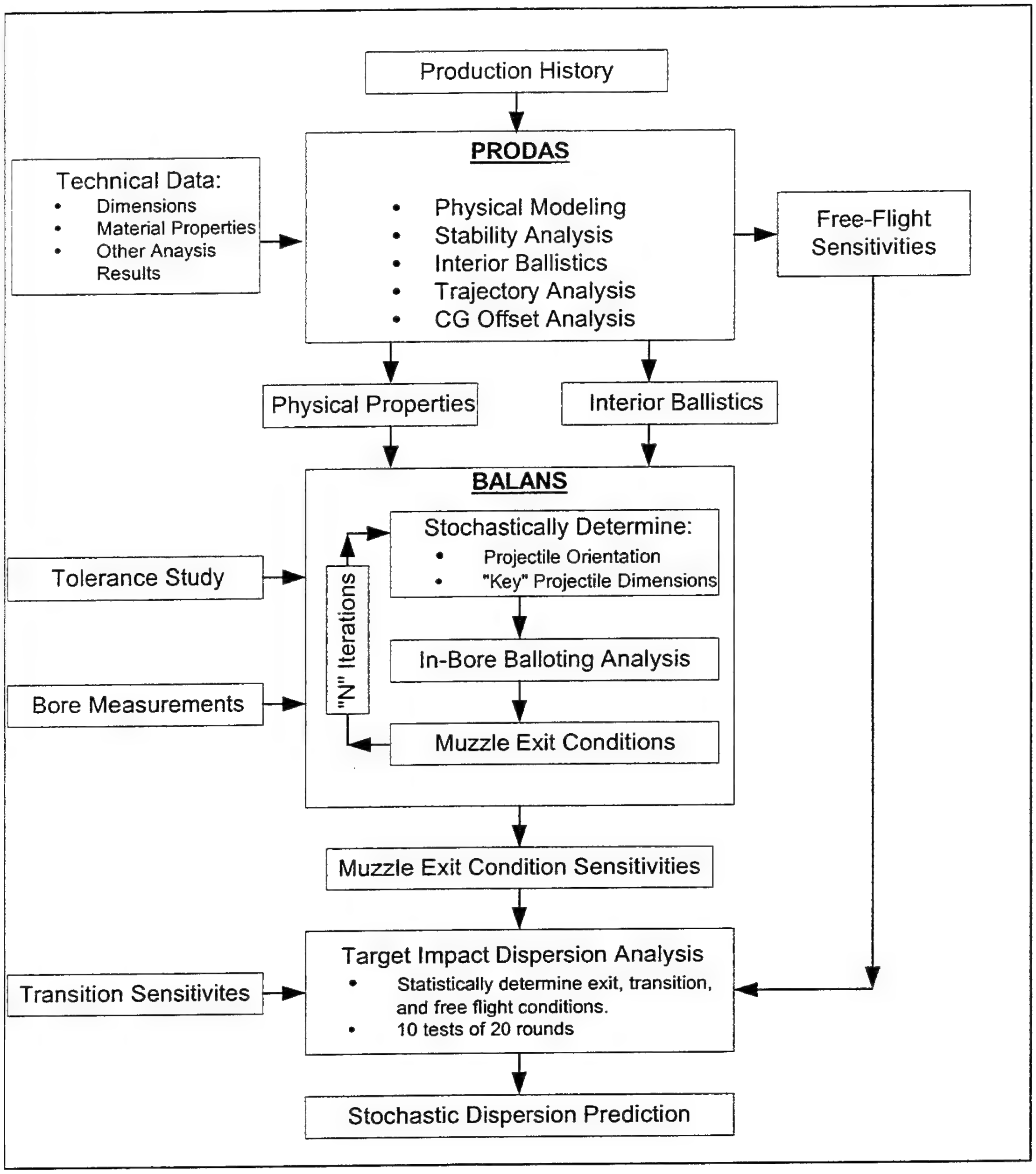

Figure 1. Analytical Approach to Predicting Dispersion.

As can be seen in Figure 1, the drawings, production history, and results from previous analyses are used for physical modeling of the projectile which, in turn, is the basis for several analyses to be described in the following sections. Each of the analyses results in dispersion component sensitivities that are then used in predicting the total dispersion.

3. Modeling

3.1 BALANS Model of the M242 25-mm Chain Gun. The standard M242 chain gun barrel is 2.0 m long. The barrel is modeled by 20 finite elements by defining 21 points along the length of the barrel geometry. Each elemental length and cross-sectional geometry determines the mass and stiffness of that element. An example can be seen in Figure 2. The two positions marked by the letter "s" in Figure 2 represent the support locations for the barrel in the gun system.

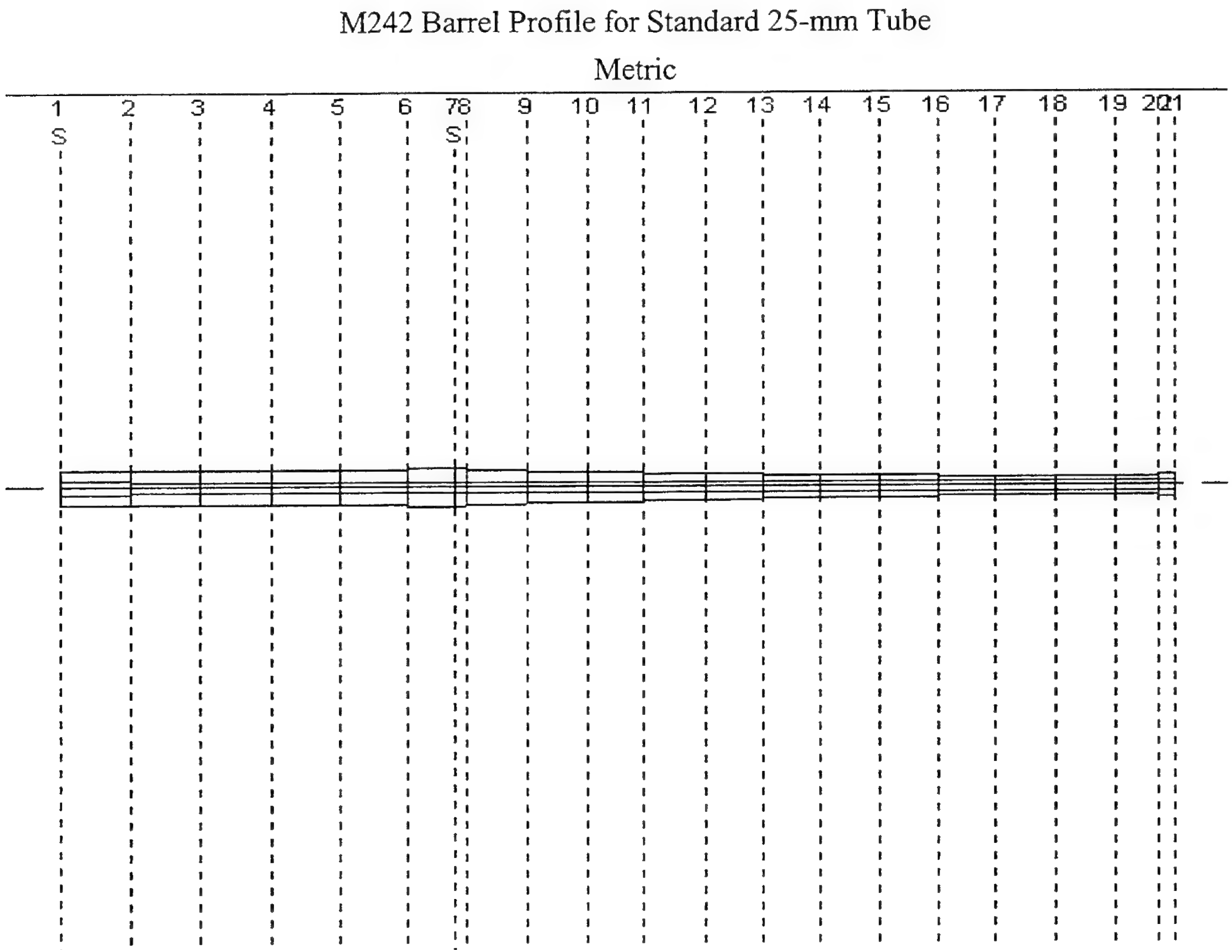

Figure 2. BALANS Representation of the M242 Gun Barrel.

3.2. Bore Straightness. The M242 chain gun, barrel serial number (SN) 273, was measured for centerline straightness and bore gauged for service condition. The vertical (without gravity droop) and horizontal centerline reference to the rear face of the tube (RFT) is shown in Figure 3. The manufacturing irregularities noted in the centerline are typical with positive up and to the gunner's right.

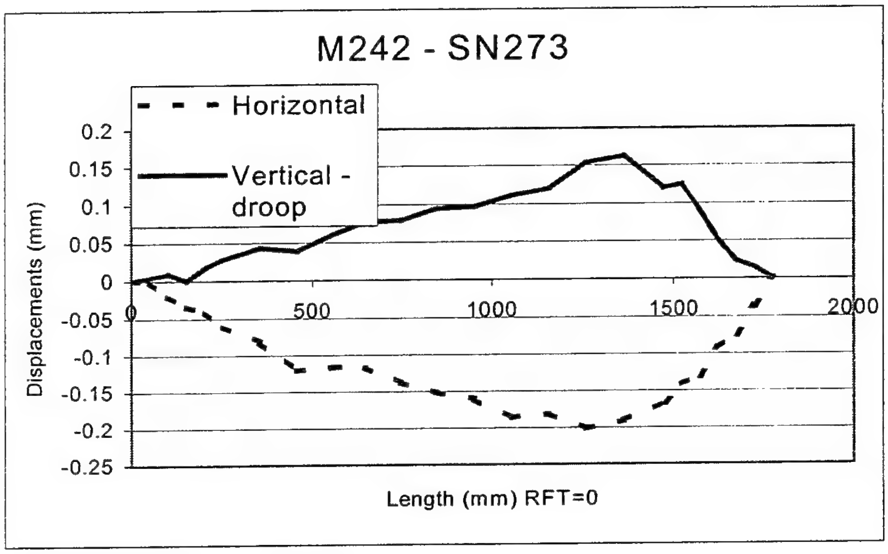

Figure 3. M242 Barrel SN 273 for the M242 25-mm Chain Gun.

3.3 BALANS Model of the XM881. The basic inputs for the in-bore balloting analysis are a lumped-parameter finite-element model of the projectile that properly characterizes its mass properties and flexibility. The forcing function is driven by the interior ballistics. Bore-rider spacing and run-out distances are used to orient the projectile within the gun tube. The lumped parameter projectile model is generated automatically from the PRODAS geometric model.

The lower half is the lumped-parameter node and element model. In the top part of Figure 4, the node numbers are displayed. Under node No. 10, the "LS" indicates that a linear spring is used to interface the projectile bulkhead to the gun barrel bore. Then, in similar fashion, an "NS" locates a nonlinear spring onto the forward bell of the sabot. The forward-bell-spring parameters are detailed in a later section.

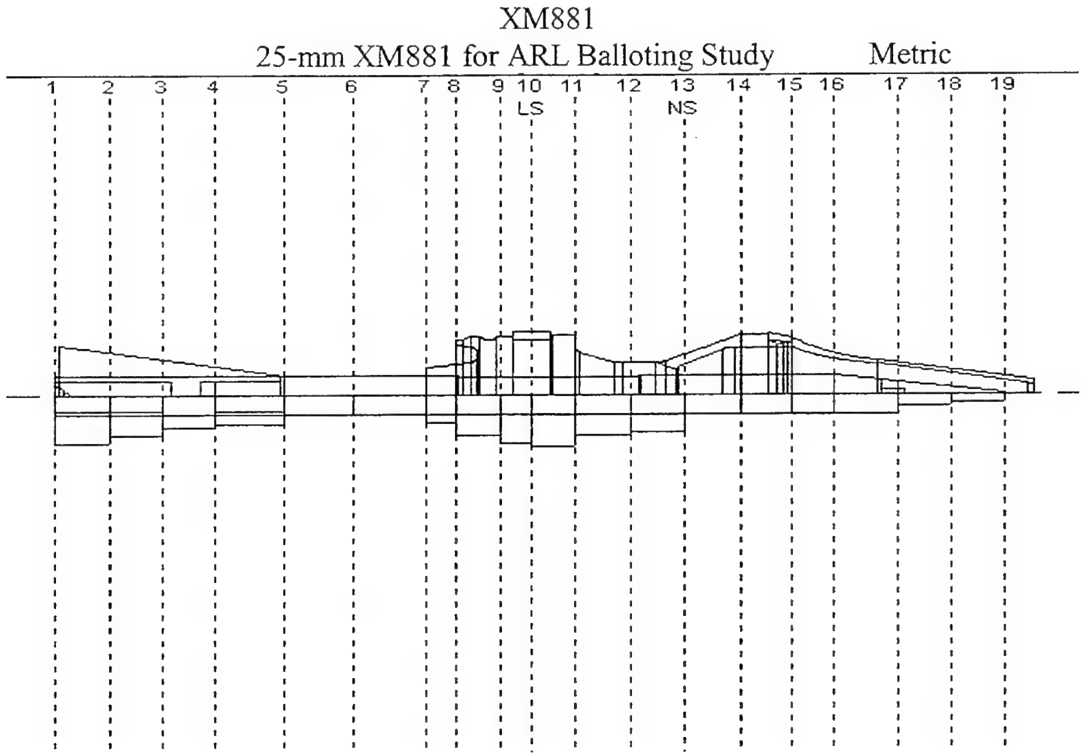

Figure 4. Graphical Representation of the XM881 Lumped-Parameter Model.

The forcing function required for the balloting analysis is provided directly from the PRODAS interior ballistics analysis module. PRODAS uses the Baer-Frankle methodology [5] to simulate combustion of propellant grains and calculate the time-dependent base pressure, spin, velocity, and axial acceleration. Transverse forces are calculated from the induced balloting motion.

Figure 4 is an example of the XM881 lumped-parameter model. As shown, the upper half of the model is the actual projectile as generated from PRODAS. In addition to the lumped-parameter model, the dispersion analysis requires manufacturing dimensional and tolerance information. The manufacturing information consists of several critical dimensions and tolerances necessary for in-bore balloting. These define the locations of the projectile/gun tube interfaces and some of the critical projectile dimensions that affect dispersion. The statistical in-bore balloting analysis uses these dimensions and their tolerances to randomly orient the projectile in the gun tube. Several hundred in-bore balloting analyses are generally

required to obtain statistically valid muzzle exit yaw, yaw rate, and transverse velocity predictions [6].

The transitional ballistics and free-flight sensitivity information is used to determine those components of dispersion after the projectile has left the gun tube. Transitional ballistics sensitivities are separated into sabot discard and bore-sight sensitivities. Errors induced by sabot discard may have significant variation from one projectile configuration to another. They have both a physical component, which can occur due to asymmetric loads applied to the core during discard, and an aerodynamic interference component. Sabot discard is the least well understood of the major contributors to dispersion and is therefore generally determined from test, observation, and/or experience. Bore-sight errors are associated with pointing the gun at the target. Bore-sight errors vary between calibers, gun crews, and instrumentation.

The free-flight dispersion sensitivities include muzzle velocity, aerodynamic jump, aerodynamic trim angle, crosswind, and aerodynamic/mass asymmetries. All of these parameters are determined via trajectory analysis within PRODAS as follows:

- The muzzle velocity sensitivity factor is the variation gravity drop due to muzzle velocity changes and can be calculated by initial free-flight trajectory simulations made by perturbating muzzle velocities.

- The aerodynamic jump sensitivity relates dispersion to the muzzle exit yaw rate of the projectile. In BALANS, the muzzle exit yaw rate is used to estimate the initial free-flight rate. This factor is dependent upon the physical and aerodynamic characteristics of the projectile as well as the projectile spin and velocity.

- The crosswind sensitivity of the projectile is determined by trajectory simulations of the projectile flight to the range of interest both with and without a nominal crosswind.

- The aerodynamic trim angle of a projectile configuration (due to manufacturing tolerances) may be calculated from PRODAS predictions of the body-alone and fin-alone center of pressure and normal force coefficients and from the expected one-sigma value of the angular misalignments of the nose and tail sections.

- The aerodynamic/mass asymmetry factor spread is determined by simulating trajectories with a trim angle assumed to be oriented at diametrically opposite positions.

3.4 Stochastic Analysis: A Set of 10 Shots Within 10 Simulations. Since production history, information such as SPC does not exist for the XM881 projectiles in the available inventory. Based on M919 data, the parameters required for input had to come from either measurements or estimates. For the sensitivity values found in Table 1, the muzzle velocity data come from the experiment. Aerodynamic jump, yaw factor, and spin rate come from the PRODAS analysis. Bore sight, sabot discard, and miscellaneous error numbers are engineering estimates based on experience with similar projectiles. For simplicity, values that were assumed to be zero, such as wind factors, aerodynamic and mass asymmetries, and others, are not shown in the table.

Table 1. XM881 Sensitivity Data

Characteristic	Value	Data Source
Aerodynamic Jump Factor (Dimensionless)	0.030	Estimated
Muzzle Velocity Standard Deviation (m/s)	8.419	Estimated
Muzzle Velocity Factor (Dimensionless)	0.005	Estimated
Bore-sight Error (Dimensionless)	0.050	Estimated
Sabot Discard Error (Dimensionless)	0.050	Estimated
Miscellaneous Errors (Dimensionless)	0.100	Estimated
Muzzle Velocity (m/s)	1398.4	Measured
Initial Yaw Factor (mils)	0.010	Estimated
Muzzle Spin Rate (rads/s)	2900.0	Estimated

Table 2 contains manufacturing tolerance information required for the simulation. Generally, these data are obtained from previous simulations, tests, drawings, and/or SPC data collected by

Table 2. Manufacturing Tolerance Information

Characteristic	Value (mm)	Data Source
Distance to Obturator	63.0941	Measured
Distance to Forward Spring	101.143	Measured
Distance to Bore Rider	110.236	Measured
Bore Diameter	25.100	Measured
Forward Bourrelet Mean Diameter	24.970	Estimated
Forward Bourrelet Standard Deviation	0.015	Estimated
Forward Bourrelet Run-out (Mean to Penetrator)	0.025	Estimated
Forward Bourrelet Run-out Standard Deviation	0.010	Estimated
Rear Bourrelet Run-out (Mean to Penetrator)	0.025	Estimated
Rear Bourrelet Run-out Standard Deviation	0.010	Estimated
Sabot Inside Diameter at Forward Bourrelet	8.273	Measured
Sabot Inside Diameter at Forward Bourrelet Standard Deviation	0.000	Estimated
Core Outside Diameter at Forward Bourrelet	8.273	Measured
Core Outside Diameter at Forward Bourrelet Standard Deviation	0.000	Estimated

the manufacturer. For these simulations, the source of the data was either through measurements (measured) or from engineering estimates (estimated), which are based on previous experience in simulating and testing of similar rounds.

The BALANS dispersion results presented in Table 3 are the result of 10 different simulations of 10 rounds each, stochastically determining projectile orientations and other key dimensions as described earlier to develop the muzzle exit conditions of yaw, yaw rate, and velocities. To perform the target impact dispersion (TID) analysis, the muzzle exit sensitivities are combined with the transitional ballistic sensitivities and free-flight sensitivities. Table 4 shows the components of dispersion for simulation No. 3.

3.5 Variation of Sabot Petal Front Bore-Rider Stiffness. The goal of this study was to ensure producing a difference in the dispersion results. Therefore, the nominal stiffness value is changed by a power of 10 above and below the nominal stiffness value. Table 5 presents the spring stiffness values used in this study.

Table 3. Simulated TID Results of 10 Simulations of 10-Round Tests From the Nominal Case

Simulation No.	Horizontal (mrad)	Vertical (mrad)
1	0.372	0.413
2	0.337	0.322
3	0.327	0.339
4	0.402	0.416
5	0.383	0.369
6	0.211	0.188
7	0.350	0.362
8	0.365	0.398
9	0.346	0.343
10	0.346	0.339
Average	0.344	0.349
Standard Deviation	0.049	0.062

Table 4. Components of Dispersion From Simulation No. 3

Dispersion Component	Horizontal (mrad)	Vertical (mrad)
Yaw Rate	0.219	0.219
Muzzle Velocity	0.000	0.269
Windage	0.000	0.000
Bore-sight	0.050	0.050
Sabot Discard	0.050	0.050
Aero/Mass Asymmetries	0.000	0.000
Yaw Angle	0.001	0.001
Transverse Velocity	0.195	0.195
Muzzle Spin	0.204	0.204
In-Bore Total (Yaw Rate + Yaw Angle + Transverse Velocity + Muzzle Spin) = 0.345		

4. Results

The BALANS dispersion results are from 10 different simulations of 10 rounds each, stochastically starting with different projectile orientations and other key dimensions. In

Table 5. Sabot Petal Front-Bell Stiffness

Measurement	Nominal	Soft Spring	Hard Spring
Metric	2,452,000 N/m	24,5200 N/m	24,520,000 N/m
English	140,000 lb/in	14,000 lb/in	1,400,000 lb/in

Tables 6 and 7, results are presented for the three different spring values used on the sabot front bell-spring. Table 6 presents results in the vertical plane, and Table 7 presents results in the horizontal plane.

The Aerodynamics Branch of ARL and Arrow Tech Associates are continuing to resolve all the parameter definitions and understand all the translations that are required to make BALANS output results correlate to the similar quantities that are used in the experimental arena. At the present time, the two parties believe horizontal and vertical standard deviations (sigmas) for total dispersion can be compared directly. Figure 5 presents all the results in Tables 6 and 7, where each symbol is a 10-round group. The dispersion from the experiment is displayed as the shaded star (∗) in Figure 5.

Table 6. Simulated TID Results in the Vertical Plane of 10 Simulations for Varied Front-Bell-Spring Stiffness

Simulations	Nominal	Hard Spring	Soft Spring
1	0.413	0.293	0.563
2	0.322	0.458	0.505
3	0.339	0.435	0.503
4	0.416	0.282	0.542
5	0.369	0.319	0.485
6	0.188	0.34	0.523
7	0.362	0.289	0.416
8	0.398	0.358	0.364
9	0.343	0.402	0.319
10	0.339	0.328	0.498
Average	0.349	0.350	0.472

Table 7. Simulated TID Results in the Horizontal Plane of the 10 Simulations for Varied Front-Bell-Spring Stiffness

Simulations	Nominal	Hard Spring	Soft Spring
1	0.372	0.355	0.535
2	0.337	0.403	0.453
3	0.327	0.393	0.5
4	0.402	0.332	0.555
5	0.383	0.326	0.41
6	0.211	0.325	0.48
7	0.35	0.296	0.399
8	0.365	0.397	0.396
9	0.346	0.38	0.364
10	0.346	0.305	0.444
Average	0.344	0.351	0.454

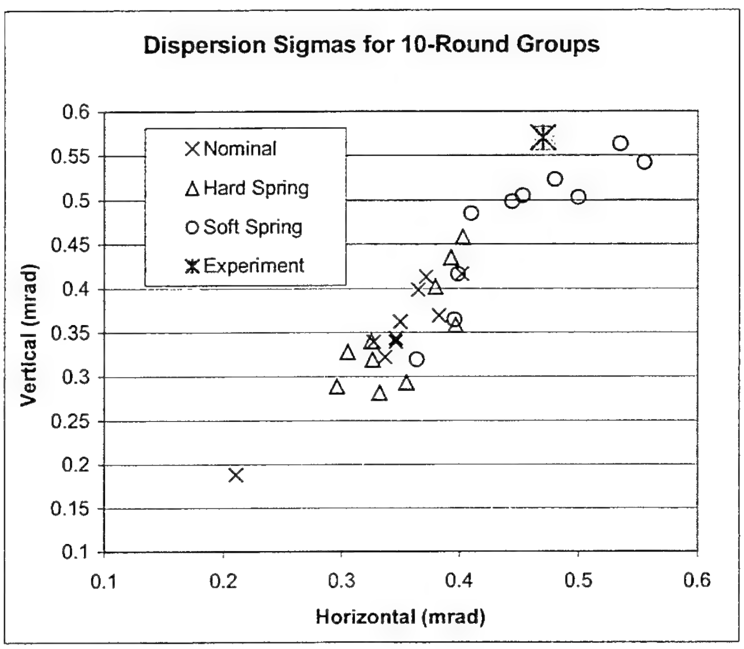

Figure 5. The Different Cases of Front-Bell-Spring Stiffness TIDs Compared to the Experimental Dispersion.

In Figure 5, the soft-spring cases tend to increase dispersion, while the hard-spring dispersions appear to fall around the nominal cases. To simplify observation of these statistical groupings, a comparison of the average dispersion values is presented in Figure 6. When

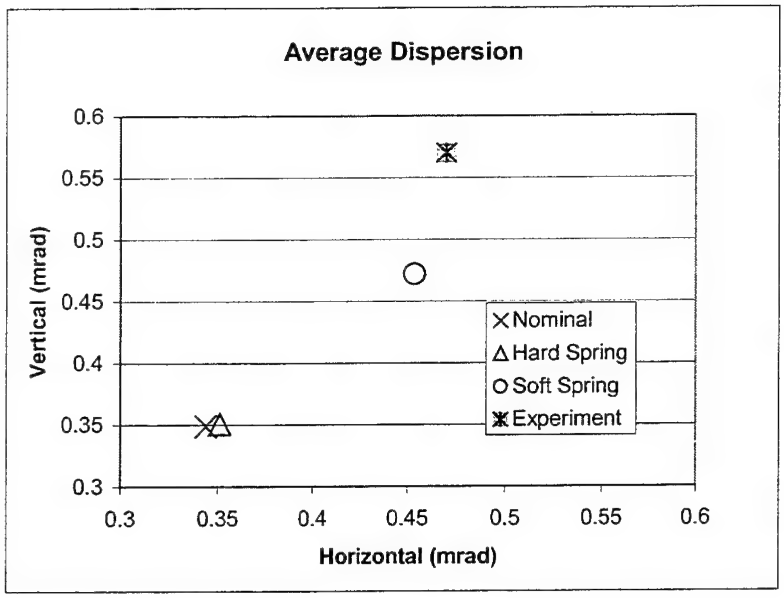

Figure 6. The Modeling Dispersion Averages Compared to the Experimental Dispersion.

comparing averages of the modeling cases, the soft-spring average is greater than the other cases. It can also be noted how the soft-spring average dispersion falls closer to the experimental value.

5. Conclusions

The BALANS models predict that the soft-spring sabot front-bell case produces a larger dispersion than nominal- and stiff-spring cases. The soft-spring case also produces the largest variation from group to group, observed as noted in Figure 5. Also noted in Figure 5, the hard- spring case dispersions appear to overlap the nominal-spring cases, with the exception of one case.

The BALANS analytical approach is useful for the investigation of variation of the sabot front-bell-spring stiffness and its effect on dispersion. Dispersion is a combination of random independent and interdependent events. Therefore, BALANS appears to be a useful tool to simulate at least the trends in dispersion by a stochastic method.

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